

# HST Photometry of 47 Tuc and Analysis of the Stellar Luminosity Function in Milky-Way Clusters

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## ABSTRACT

We present V and I photometry for over 1000 stars in a region 5' from the center of the globular cluster 47 Tuc. The field was imaged with the *Wide Field and Planetary Camera - 2* as part of the Hubble Space Telescope's Medium Deep Survey key project. The luminosity function (LF) continually rises in the domain  $5 \lesssim M_I \lesssim 9$  with a slope  $\Delta \log \Phi(M)/\Delta M \sim 0.15$  and then drops off sharply. We compare our luminosity function with that derived by De Marchi & Paresce for a neighbouring HST field. The two independent LFs are remarkably similar in the entire range of luminosities probed ( $M_I \lesssim 10$ ). Comparisons are also made to other HST LFs derived by several authors for both globular and open clusters in the Galaxy. We use the KS test to assess the significance of the differences found. The luminosity distributions obtained with HST are consistent with being derived from the same population down to  $M_I \sim 9.0$ . Beyond that, statistically significant variations arise. Globular cluster LFs also differ according to the prominence of a plateau in the bright end ( $5 \lesssim M_I \lesssim 6.5$ ). The mass functions are rather uncertain and sensitive to the mass-luminosity relation. Different approaches to deriving the 47 Tuc mass function from its LF lead to markedly different results at the low mass end. For  $M \gtrsim 0.4M_\odot$ , the 47 Tuc mass function is significantly different from that of  $\omega$  Cen. The calibrated HST  $M_V(V-I)$  colour-magnitude diagrams (CMDs) show a trend with metallicity in the expected sense of metal richer systems having redder CMDs for a fixed absolute magnitude. The main-sequence slope becomes shallower with increasing metallicity. The CMDs derived from HST are in general agreement with previous ground-based studies, especially for metal rich stars. However, the CMDs of metal poor subdwarfs observed from the ground are shallower than those of globular clusters observed with HST. This discrepancy may either result from calibration problems of HST data or reflect real differences between the CMDs of globular cluster and field halo stars.

## 1 INTRODUCTION

The determination of a Globular cluster’s luminosity function is a first step towards deriving its present day mass function (PDMF). The latter in turn contains potential information about the initial mass function (IMF) and about the role played by several dynamical processes such as dynamical friction, evaporation and tidal stripping over a cluster’s lifetime (Elson, Hut & Inagaki 1987, Aguilar 1993). Knowledge of the low-mass end of the IMF may help modeling star formation processes and the physics of stellar interiors and atmospheres (Larson 1992, D’Antona 1994). Given the similarity between the kinematical and chemical properties of globular clusters and the stars in the halo of our Galaxy, the study of the globular cluster luminosity and mass functions may also provide clues to the formation and evolution history of this latter component.

Derivation of a cluster PDMF from luminosity functions requires knowledge of the relation between mass and luminosity for its component stars. Direct mass determinations are available for relatively few disk binaries, mostly nearby and of solar abundance (Popper 1980). Thus, given that the mass-luminosity relation is a function of metallicity and age, mass-luminosity relations must usually rely on models of stellar atmospheres (D’Antona & Mazzitelli 1986, D’Antona 1987, Bergbusch & Vandenberg 1992, Saumon *et al.* 1994). Such purely theoretical predictions suffer from substantial uncertainties, especially for low-mass low-metallicity stars, for which relatively few high signal-to-noise spectra have been obtained in order to constrain the theory.

On the observational side, reliable derivation of stellar LFs down to faint absolute magnitudes ( $M_V \sim 14$ ) has been mostly restricted to field stars (Wielen *et al.* 1983, Stobie *et al.* 1989). Most previous determinations of the luminosity function (LF) in globular clusters have been based on observations made from the ground, thus suffering from crowding effects. Fahlman *et al.* (1989) and Richer *et al.* (1991) found evidence of steeply rising mass functions at the low-mass end of several globulars. Their ground-based data, however, required large and uncertain completeness corrections at the low-luminosity (mass) end. More recently, data from the Hubble Space Telescope (HST) have become available as the result of several independent studies (Paresce, De Marchi & Romaniello 1995, Elson *et al.* 1995, De Marchi & Paresce 1995a,b). Given the 0.1” resolution of the *Wide Field and Planetary Camera 2* (WFPC-2), these HST data allow globular cluster luminosity functions to be pushed towards much fainter magnitude levels without the need for large completeness corrections. Most of the LFs derived with HST show a clear decline at faint magnitudes, in conflict with the ground-based work. There also seems to be a general agreement in the shape of the LF at bright and intermediate luminosities, even when systems of completely different chemical abundances, ages and dynamical histories are compared (such as the disk field stars *vs* halo globulars, see Elson *et al.* 1995). It is thus important to confirm this result using the increasing amount of available HST data, and to quantify the possible differences in the low luminosity end.

In this paper we present data obtained for 47 Tuc as part of the Medium Deep Survey HST key-project (MDS, see Griffiths *et al.* 1994). We compare the derived colour-magnitude diagram (CMD) and luminosity function to those obtained by several other authors using HST. We assess the differences in the observed LFs by means of the Kolmogorov-Smirnov (KS) test. In spite of the lack of knowledge about the mass-luminosity relation and its dependence on metallicity (especially for low mass stars), we also attempt to derive the PDMF for the 47 Tuc

data and to compare it to the PDMF of other clusters. In §2, we present the data and discuss the accuracy of our photometry. In §3 we show the LF for 47 Tuc and compare it to those of other clusters. In §4, we do the same analysis for the mass functions. and also present CMDs. Finally, in §5 we present our conclusions.

## 2 THE DATA

### 2.1 The field and sample selection

The WFPC-2 field was observed on Sep. 29 1994 in parallel mode. It is located 4.8' east and 1.3' north of the cluster center, at a distance corresponding to about  $0.8 r_h$ , where  $r_h$  is the half-mass radius (Meylan 1989). A total of 8 exposures was made with both HST wide I (F814W) and V (F606W) filters. All frames were put through the standard pipeline procedure which accounts for dark current and bias level subtraction, flat-fielding and correction for several other instrumental effects (Holtzman et al 1995a). The first 4 frames taken with each filter are spatially offset to the south by 25" relative to the last 4 frames. This offset is large enough to lead to a significant loss of area if all 8 exposures are coadded together. Thus, we decided to coadd each set of 4 exposures separately; the frames in each set were scaled to a common exposure time and the lower median pixel intensity used at each position. This method has been successfully applied to HST images in several previous works (Glazebrook et al 1995, Elson *et al.* 1995, Elson & Santiago 1995,1996, Santiago *et al.* 1996) and we are indebted to K. Glazebrook for developing the IRAF script that performs this task. The total exposure time for each set was 4000s in the I and 3200s in the V band. Hot pixels were not eliminated during the coadding phase and were not flagged out either, but were eliminated subsequently (see below). No correction was applied for the charge transfer efficiency (CTE) problem, since our data were taken at a CCD temperature of  $-88^\circ$ , in which case this is a small effect in the photometry (Holtzman *et al.* 1995b). The two final coadded images in each filter overlap over more than 2/3 of the 3 WFC-2 chips. The WFC chips are also more affected by crowding, since their spatial resolution is smaller. We thus restricted our analysis to the smaller field, higher-resolution PC chips, where the overlap region represents 22% of the CCD area. We used the objects in this common region to assess the accuracy of our photometry. We hereafter refer to the two distinct but overlapping regions imaged with the PC in both filters as Fields 1 and 2.

The IRAF package DAOPHOT was used to obtain object lists and perform the photometry. We adopted a procedure very similar to that described in Elson *et al.* (1995). Our primary object list was obtained by running the DAOPHOT task DAOFIND on the F814W coadded images of both Fields 1 and 2. A total of 3530 sources were found by the DAOFIND task in Field 1. Field 2 contributed with an additional 3859 objects. Most of the sources detected, however, turned out to be features around the psf of bright stars or hot pixels. These features are structurally different from point sources imaged with the PC chips and were easily eliminated on the basis of their shape and on their poor fit to the HST-PC point spread function (psf). The shape of this latter was obtained by fitting a Moffat function with  $\beta = 1.5$  to about 20 bright and isolated stars in each field. The resulting psf was then fitted to all sources detected and those with large  $\chi^2$  values or elongated shapes were eliminated. DAOPHOT assigns a magnitude for each source by scaling the psf template so as to match source's intensity

profile. Since the psf template’s magnitude was obtained from aperture photometry on a 2 pixel radius around bright isolated stars, an aperture correction had to be applied in order to account for the light outside this radius. This correction was estimated directly from the same bright isolated stars used to build the psf and showed very little variation from star to star. It also corresponds to those quoted by Holtzman *et al.* (1995a). The aperture corrections amounted to 0.5 mag in the V filter and 0.6 mag in the I filter.

We visually inspected the remaining objects and almost all of them had shapes consistent with being stars. However, some residual non-stellar features still remained close to very bright, saturated stars; they were eliminated by defining exclusion zones in the vicinity of such objects. Our final stellar lists contained 779 and 763 objects in fields 1 and 2, respectively. 151 of these objects ( $\sim 20\%$ ) are in common between the two PC fields, very close to the expected number considering the size of the overlapping area.

For the F606W frames we adopted essentially the same procedure, except for the fact that we used the same primary object lists as in the F814W frames. The shape of the F606W psf was obtained independently, again by fitting a Moffat function to several bright isolated stars and creating a template. Magnitudes, shape parameters and  $\chi^2$  values were then obtained for all sources by fitting the template psf. Using the same criteria as for the I band, 685 sources in field 1 were found to be stars. Field 2 contributed with 671 stars in V, 135 in common with Field 1.

## 2.2 The photometric accuracy

Figure 1 shows a comparison between the magnitudes obtained for the stars in common between fields 1 and 2. The zero-points applied to these magnitudes were those listed by Holtzman *et al.* (1995a) in order to transform the WFPC-2 flight data into the WFPC-1 system defined by Harris *et al.* (1991). We did not apply any colour terms at this stage, since they are small ( $< 0.1$  mag). The agreement between the two sets of magnitude measurements is excellent for both filters. The scatter in panel *a* is less than 0.04 for  $I_{814} < 20.5$ , increasing continuously towards faint magnitudes up to 0.14 for  $I_{814} \gtrsim 22.5$ . Similar values are found for the scatter in the  $V_{606}$  magnitudes. There is a very small ( $\sim 0.04$ ) mean offset between the magnitudes in the two fields, in the sense that field 2 values are fainter. This is consistent with the amplitude and direction of the CTE effect in the HST chips, since the common stars between the two fields are located at high (low) row numbers in field 2 (field 1). Given its small amplitude, we did not correct for this offset.

In Figure 2 we show the colour-magnitude diagram for the composite data of fields 1 and 2. Only objects that were successfully classified as stars in both I and V frames are included. Stars brighter than  $I_{814} = 18.5$  were eliminated to avoid saturation problems. A total of 1121 stars are shown in the figure. There are two very distinct loci in the diagram. Most stars lie along the 47 Tuc main sequence but many are seen on the lower left of the plot. These later belong to the Small Magellanic Cloud (SMC) and can be clearly separated from the cluster stars. The main sequence is fairly well defined, showing a scatter in colour smaller than that of De Marchi & Paresce (1995b), whose data correspond to a nearby field also imaged with HST. This is consistent with our larger exposure times. The broadening of the main-sequence at  $I_{814} < 19$  is due to residual saturation effects. Even though most saturated stars were automatically thrown away because of their poor fits to the PC psf, some objects whose peaks

are slightly saturated have remained. There is also a hint of a main-sequence curvature at the bright end, which is caused by the turn-off at  $V_{606} - I_{814} \sim 0.5$ .

From Figure 2, we can also identify a parallel sequence of stars lying above the main sequence. These objects are consistent with being unresolved equal mass binaries, whose composite magnitude would thus lie 0.75 mag above the main sequence. Based on their number we estimate the equal mass binary fraction at this radius in 47 Tuc to be  $\sim 5\%$ . Finally, we also confirm the steepening in the main-sequence (at  $I_{814} \sim 21.5$ ), as noticed by De Marchi & Paresce (1995b) for the same cluster. This observed “kink” is related to changes in stellar interiors which affect the temperature-luminosity relation (Copeland *et al.* 1970).

### 3 LUMINOSITY FUNCTIONS

The I band luminosity function derived from the 1050 stars found to lie along the main sequence of Figure 2 is shown in Figure 3. We assumed a distance modulus of  $(m - M) = 13.46$  for 47 Tuc when converting  $I_{814}$  into absolute magnitudes (Madore 1980). We also applied an extinction correction of  $A_{814} = 0.08$ , consistent with  $E(B - V) = 0.04$  (Hesser *et al.* 1987) and Table 12B of Holtzman *et al.* (1995b). The error bars in the figure are Poissonian and the luminosity function is expressed as number of stars per unit magnitude. One can estimate the slope of the LF brighter than the turn over, where completeness corrections are likely to be irrelevant. We obtain  $\Delta\Phi/\Delta M_{814} \simeq 0.15$  for  $M_{814} < 9$ . This is in excellent agreement with De Marchi & Paresce (1995b).

The effect of incompleteness was assessed with the help of simulations. We used the ADDSTAR task in DAOPHOT for that purpose. Five simulations with 200 artificial stars each were made for each one of 16 magnitude bins within the range  $19 < I_{814} < 27$ . The stars were added to the real data frame and the resulting image was put through the same object detection and star selection procedure described above. Magnitudes were also obtained by psf fitting, as for the real data. For each simulation, we estimated the fraction of artificial stars recovered and whose magnitudes agreed within 0.5 mag with the input ones. Notice that the completeness function derived this way quantifies the loss of stars solely due to our detection threshold in the F814W frames. We are, however, restricting our analysis to those stars for which a  $V_{606}$  magnitude was also available. In order to incorporate the loss of stars caused by this additional constraint, the completeness function derived from the simulations had to be multiplied by the fraction of main sequence stars detected in  $I_{814}$  for which a  $V_{606}$  magnitude was successfully measured,  $f_V(I_{814})$ . This latter quantity is not easy to quantify, since we do not know what the contamination of SMC stars at each  $I_{814}$  magnitude is in the original object list. We derived values for  $f_V(I_{814})$  using two extreme assumptions: *a*) completely overlooking the presence of SMC stars in the original object list and computing  $f_V(I_{814})$  as the ratio of the number of main sequence objects shown in Figure 2 to the total detected in the  $I_{814}$  frames. This leads to an underestimate of  $f_V(I_{814})$ ; *b*) assuming that the ratio of main-sequence/SMC stars in the original list is the same as in Figure 2, which tends to overestimate  $f_V(I_{814})$ ; the MS/SMC ratio in Figure 2 must be smaller than in the original list since the loss of objects due to lack of V band detection will be more severe for faint (red) main-sequence stars than for faint (blue) SMC stars. The final value of  $f_V(I_{814})$  was taken to be the mean of these two. Even for our faintest data bin ( $I_{814} \sim 24$ ,  $V_{606} \sim 26$ ), these two extreme values of  $f_V(I_{814})$  agree within 20%.

The final completeness function is shown in Figure 4 for both fields 1 and 2. The two completeness curves are similar, with the data being essentially complete for  $I_{814} \sim 20.5$  ( $V_{606} \sim 21.5$ ) and still nearly 50% complete for 2.5 magnitudes fainter than that. Beyond  $I_{814} \sim 23.5$  ( $V_{606} \sim 25.3$ ) incompleteness becomes severe, in agreement with the increasing paucity of faint stars along the main sequence in Figure 2. The error bars in Figure 4 are the composition of the standard deviations in the completeness fractions for the 5 simulations carried out for each magnitude bin and the uncertainty associated to  $f_V(I_{814})$ . Note that field 2 has a slightly steeper completeness function, consistent with it being slightly more crowded than field 1.

In Figure 5 we plot the luminosity function corrected for incompleteness. Its shape is very similar to the uncorrected one (Figure 3), except for the slower drop in the number of stars at the faint end. The decreasing trend in the luminosity function of Figure 5 for magnitudes fainter than  $I_{814} \sim 9$ , however, is still quite clear. The error bars take into account both statistical fluctuations and uncertainties in the completeness corrections. Also shown in Figure 5 is the 47 Tuc HST data from De Marchi & Paresce (1995b) for another field some 5' from the cluster center. The latter LF was normalized to our LF in the range  $5.5 < M_{814} < 8.5$ . The two curves are remarkably similar over all the common range in  $M_{814}$ , adding confidence to the reality of the observed features.

We now consider how the 47 Tuc LF in our field compares with those of other globular clusters. In Figure 6, we plot the completeness corrected 47 Tuc LF again, along with those derived by Elson *et al.* (1995) for  $\omega Cen$  and Paresce *et al.* (1995) for NGC 6397; all these works are based on HST data. We thus avoid the issue of calibration to the standard (Johnson-Cousins) photometric system and show all the data in  $M_{814}$ . For  $\omega Cen$ , we use the raw data from Elson *et al.* (1995) and adopt a distance modulus of (m-M)=13.92, as quoted by Madore (1980). This is slightly different from the value used in Elson *et al.* (1995). The 2 fields analyzed by these authors are located at about 12' and 17' from the cluster's center ( $\sim 3.2 r_h$  and  $\sim 4.6 r_h$ , respectively). The data for N6397 come directly from Paresce *et al.* (1995), who studied a field some 0.6  $r_h$  from the center. Both  $\omega Cen$  LFs have been normalized to the 47 Tuc one in the range  $5.5 < M_{814} < 8.5$ . For Paresce *et al.* (1995), the normalization was within the range  $6.5 < M_{814} < 8.5$ .

All 4 LFs shown in Figure 6 seem to have similar shape within the region used for normalization ( $6 \lesssim M_{814} \lesssim 8.5$ ). Outside this range significant differences arise between the  $\omega Cen$  and 47 Tuc data. The  $\omega Cen$  LFs have a clear plateau in the range  $5 < M_{814} < 6.5$ , whereas the 47 Tuc data rise with nearly constant slope. At the faint end, the  $\omega Cen$  LF seems to flatten out, whereas the 47 Tuc is clearly declining. The N6397 data are in close agreement with the 47 Tuc LF over the entire range of magnitudes. The same conclusion applies to the LF obtained by De Marchi & Paresce (1995a) for M15, which is not shown in figure 6 for clarity. In fact, as pointed out by these authors, the N6397 and M15 LFs are remarkably similar, rising to a maximum at  $M_{814} \simeq 8.6$  and dropping-off sharply for fainter luminosities.

How significant are the differences between the  $\omega Cen$  and 47 Tuc LFs? In order to answer this question we use the Kolmogorov-Smirnov test. In Table 1, we list the results of applying the KS test to the 47 Tuc and  $\omega Cen$  data. Columns 1 and 2 list the LFs being compared and column 3 the range in absolute magnitude ( $M_{814}$ ) used. Columns 4 and 5 give the number of points within this range (including completeness corrections) and column 6 lists the probability

that the two LFs are drawn from the same ensemble. The first two lines show that the data from the two 47 Tuc PC chips lead to perfectly consistent LFs. We are thus entitled to put the 47 Tuc data together as we have done. We also compared the two  $\omega$  Cen fields; the results indicate that the two  $\omega$  Cen LFs are consistent with each other over most of the available range in  $M_{814}$ . However, the two LFs seem to be significantly different beyond  $M_{814} \sim 9.5$ , which corresponds to the faintest bin in field 1 shown in Figure 6 (notice that Elson *et al.* data extend down to  $M_{814} \sim 10.4$ ).

As for the 47 Tuc *vs*  $\omega$  Cen comparison, the results are more strongly dependent on the domain in  $M_{814}$  used and on the particular  $\omega$  Cen field being considered.  $\omega$  Cen field 1 is marginally consistent ( $P \sim 10 - 15\%$ ) with 47 Tuc for  $M_{814} \lesssim 9$ . If the faintest bins in Figure 6 are included, however, the two datasets seem to differ at a much higher confidence level. The LFs of  $\omega$  Cen field 2 and 47 Tuc are more similar: for  $M_{814} < 9.5$ ,  $P \sim 30 - 70\%$ , depending on the particular range in  $M_{814}$  used. At the faint end, however, the disagreement again becomes increasingly larger, confirming the visual impression from the figure. Finally, the differences in the “plateau region” at the bright end are statistically significant only for the  $\omega$  Cen 1 LF ( $P \sim 5\%$ ). For the comparison between  $\omega$  Cen 2 and 47 Tuc,  $P > 50\%$  for  $5 < M_{814} < 7$ , but the number of objects is significantly reduced.

We have also compared the 47 Tuc and  $\omega$  Cen LFs to that obtained by von Hippel *et al.* (1995) for NGC 2477, again using HST. The latter is an open cluster of nearly solar metallicity. The same authors also obtained V and I data for another open cluster, NGC 2420, but the number of points available is small, rendering the LF rather uncertain. The LFs for both N2477 and N2420 are shown in Figure 3 of von Hippel *et al.* (1995). The KS results involving N2477 are shown in Table 2. The conclusions are more uncertain, given the small number of stars available in the comparison. The range in magnitudes in common is also restricted since the N2477 data do not extend brighter than  $M_I \sim 8$ . The N2477 data rise out to  $M_V \sim 12.5$  ( $M_I \sim 10$ ) being thus at variance with the turnover seen in the 47 Tuc LF ( $P \lesssim 25\%$ ). For  $\omega$  Cen *vs* N2477 comparison  $P$  is consistently larger ( $\sim 30\%$ ).

In brief, variations in shape are observed in the LFs of Milky-Way clusters at both extremes of the observed range in luminosities, most especially at the faint end. For  $M_I \lesssim 9$ , the LFs discussed here are still at least marginally consistent with one another. The shape of the LF does not seem to correlate with metallicity, since the N6397, M15 and 47 Tuc all have remarkably similar LFs but very different metallicities (N6397:  $[Fe/H] \simeq -1.91$ , M15:  $[Fe/H] \simeq -2.26$ , 47 Tuc:  $[Fe/H] \simeq -0.6$ , Djorgovski 1993). Furthermore, the 2  $\omega$  Cen LFs are significantly different from those of the other 3 globulars, despite its intermediary metal abundance ( $[Fe/H] \simeq -1.6$ ). If the mass-luminosity relation depends only and smoothly on metallicity, we can expect the PDMFs not to correlate with metallicity either. The 5 LFs discussed here were also obtained at different half-mass radii, ranging from  $0.6 r_h$  to  $4.6 r_h$ . In this case, dynamical evolution due to both internal and external processes such as mass segregation and tidal stripping may have shaped the mass function of each cluster in different ways. The coupling of variable dynamical history plus variations in the mass-luminosity relation (especially as a function of metal content) clearly render as only tentative any conclusion regarding the differences and similarities among the present and initial mass functions of these clusters from their LFs alone. In the next section we try to derive the PDMF for 47 Tuc and compare it with that  $\omega$  Cen, assessing the reliability of the PDMFs.

## 4 MASS FUNCTIONS AND COLOUR-MAGNITUDE DIAGRAMS

### 4.1 The 47 Tuc mass function

Determining the PDMF requires usage of a mass-luminosity relation. We adopted here two alternative  $M_I - mass$  relations: the one shown in Figure 4 of De Marchi & Paresce (1995b) and the  $M_V - mass$  relation corresponding to the 14 Gyr,  $[Fe/H] = -0.65$  isochrone given by Bergbusch & Vandenberg (1992), with  $M_V$  magnitudes converted to  $M_I$  by using the  $M_I(V - I)$  relation for the sequence of dwarfs and mild subdwarfs of Monet *et al.* (1992). In fact, De Marchi & Paresce (1995b) used the same  $M_V - mass$  relation but applied a different conversion from  $M_V$  to  $M_I$ . Stars as metal poor as  $[Fe/H] \sim -1$  are likely to be included in the Monet *et al.* (1992) sequence, although most should have nearly solar metallicity; this range in metallicity nicely brackets that of 47 Tuc. The  $M_{814}$  magnitudes have been converted to  $M_I$  using the calibration proposed by Holtzman *et al.* (1995b) (see §4.2). Rather than multiplying the LF shown in Figure 5 by the slope of the adopted  $M_I - mass$  relation, we have directly computed the mass for each star and then binned the data in mass (in solar units).

The two mass functions derived for 47 Tuc are shown in Figure 7a. The squares use the relation provided by De Marchi & Paresce (1995b). Since we have less data, our results are noisier. Yet, our mass function is in qualitative agreement with that shown by these latter authors: an increasing mass function down to  $0.3 M_\odot$  and a flattening for smaller masses. Notice, however, that a slightly increasing mass function cannot be ruled out even at the low-mass end. This actually also applies to the De Marchi & Paresce data. Adoption of the alternative conversion from  $M_V$  to  $M_I$  leads to a clearly increasing mass function for 47 Tuc. Notice that the uncertainties in the  $M_V - mass$  relation of Bergbusch & Vandenberg (1992) are not reflected in the two mass functions shown. Incorporation of such uncertainties would further reduce the reliability of the mass function for low mass stars. We thus conclude that the low-mass end of the 47 Tuc mass function is subject to substantial uncertainty. Similar conclusions were obtained by Elson *et al.* (1995) for the  $\omega$  Cen cluster.

Despite the obvious difficulties in determining the mass of low-mass stars from their I band magnitudes, a fairly reliable computation of the PDMF can still be made for higher masses ( $\gtrsim 0.4 M_\odot$ ). In this range, the two different mass functions of 47 Tuc are in agreement. In figure 7b we compare the 47 Tuc PDMF to that of  $\omega$  Cen. The latter was determined by Elson *et al.* (1995) using the  $M_I - mass$  relation given by Brewer *et al.* (1993). It is clearly much flatter than that of 47 Tuc for  $M \gtrsim 0.3 M_\odot$ .

### 4.2 CMDs and the calibration of HST data

In this section we take advantage of the fact that we have HST CMDs for four clusters spanning a large range in metallicity, and investigate how reliable the proposed calibration schemes from the HST filters to the Johnson-Cousins system are. An appropriate transformation should lead to a trend in the loci occupied by the main-sequence CMDs as a function of metallicity in the sense that more metal rich clusters should have redder main sequence colours at a fixed absolute magnitude. We should also be able to check for the external consistency of the HST calibration by comparing the calibrated CMDs with those obtained from ground-based observations using the standard filters.



Figure 8 shows CMDs for  $\omega$  Cen, 47 Tuc, N2420 and N2477 in a sequence of increasing metallicity. The open clusters have been calibrated by von Hippel *et al.* (1995), using the prescriptions given by Holtzman *et al.* (1995a). For the more metal poor stars in  $\omega$  Cen and 47 Tuc, we used the synthetic transformations listed in Holtzman *et al.* (1995b). All 4 panels correspond to reddening-corrected data. From the figure, one can notice a clear trend with metallicity in the expected direction: metal rich systems have redder main-sequences than metal poor ones. We have also calibrated and fitted the main-sequence locus of M15, using the fiducial points listed in Table 1 of De Marchi & Paresce (1995a) and the transformations of Holtzman *et al.* (1995b). The M15 data were dereddened assuming a  $E(B - V) = 0.11$  as quoted by the authors. The main-sequence of M15 is consistently bluer than that of  $\omega$  Cen, in accordance with the expected trend in metallicity ( $[Fe/H] = -2.26$  for M15, Djorgovski 1993). M15,  $\omega$  Cen, 47 Tuc and N2477 all have main-sequences well described by two straight lines, specially in face of the observational scatter in their CMDs. Only the relatively sparse data for N2420 seem to be consistent with a single straight line. Linear fits to the main-sequences of all 5 clusters are shown in the first part of Table 3. The 4 cases fitted by a double line show a steepening in their main-sequences, the slope in the faint range of  $M_V$  being larger than that in the bright end. There is also a clear trend of both slopes to become steeper with metallicity.

The HST CMDs have been compared to those obtained by several authors using ground-based data in the standard Johnson-Cousins system (Leggett 1992, Richer & Fahlman 1992, Monet *et al.* 1992, Brewer *et al.* 1993). Linear fits were also made to these latter (or taken from the original references) and are shown in the second part of Table 3. For metal rich systems, the loci of the calibrated HST data are in good agreement with those derived from previous observations; the fits to the dwarf main-sequences of Stobie *et al.* (1989) and Monet *et al.* (1992) are well bracketed by those of N2420 and N2477. This is again indication that the HST data have been correctly converted to the Johnson-Cousins system.

The N3201 data of Brewer *et al.* (1993), available for  $M_V \lesssim 8.5$ , also fit nicely into the trend between main-sequence slope and metallicity followed by the globular clusters observed with HST; N3201 has a metallicity  $[Fe/H] = -1.3$ , being thus more metal rich than M15 and  $\omega$  Cen but much more metal poor than 47 Tuc. The intercept is, however, too small, making the N3201 stars  $\sim 0.5$  mag brighter at a fixed colour than expected from the HST calibration. The other ground-based CMDs of metal poor stars also show disagreement with those of the HST globulars. As shown in Table 3, the subdwarfs CMDs have slopes  $a \sim 3.1 - 3.5$ , being much flatter than those derived from HST data or N3201. The CMDs of Leggett (1992) and Richer & Fahlman (1992) have very similar slopes and intercepts. On the other hand, the CMD of the subdwarfs in Monet *et al.* (1992) has a larger intercept, being about 1 mag fainter at a fixed V-I colour. This had previously been noted by Richer & Fahlman (1992), who attributed the discrepancy to differences in metallicity, Monet *et al.* subdwarfs being extreme cases of metal-poor ones. As for the discrepancy between the ground-based CMDs and those from the HST, it could indicate problems in the HST “synthetic” calibration for metal-poor stars. Alternatively, it may reflect real differences between the CMDs of globular cluster and field halo populations.

## 5 CONCLUSIONS

We have presented HST V and I photometry for over 1000 stars located in a field about 5' from the center of 47 Tuc. The derived CMD and LF are similar to that shown by another recent work on the same cluster (De Marchi & Paresce 1995b); the LF rises continuously down to  $M_I \sim 9$ , with a slope  $\Delta\Phi/\Delta M_I \simeq 0.15$  and drops-off at fainter luminosities. The CMD shows a clear and narrow main-sequence down to  $M_V \sim 13$  with a change in slope occurring at  $M_V \sim 9$ . A small equal-mass binary main sequence is also present, amounting to about 5% of the stars.

By quantitatively comparing several LFs recently obtained with HST, we conclude that a universal shape of the stellar LF cannot be ruled out for  $M_I \lesssim 8.5 - 9$  (roughly  $M \gtrsim 0.3 - 0.4 M_\odot$ ) with the present data. However, a plateau is seen in the  $\omega$  Cen LF for  $5 \lesssim M_{814} \lesssim 7$  but not in the other clusters whose LFs are compared. This feature is likely to be statistically significant, according to our analysis. Globular clusters with metallicities both higher (47 Tuc) and lower (M15 and N6397) than that of  $\omega$  Cen do not exhibit this plateau, suggesting that variations in metallicity are not responsible for the existence of this feature. A similar conclusion applies to the differences seen in the low-luminosity end of the LFs: whereas 47 Tuc, N6397 and M15 show a clear turn-over,  $\omega$  Cen does not. At the faint end, the differences observed between 47 Tuc and  $\omega$  Cen are significant with more than 90% confidence. Disturbingly enough, significant differences at the faint end of the LF were found even within the  $\omega$  Cen data alone. Therefore, we conclude that the overall shape of the PDMF in clusters is largely insensitive to metallicity unless any metallicity effect is compensated for by variations in the mass-luminosity relation so as to lead to similar shapes for the LF of different metallicities. The LF for the open cluster NGC 2477 (von Hippel *et al.* 1995) was also compared to those of the 47 Tuc and  $\omega$  Cen, but the results are not conclusive due to the small number of stars available in these comparisons. We should point out that it is imperative that LFs of additional clusters with different metallicities are obtained to confirm the conclusions presented here.

We have attempted to derive the PDMF of 47 Tuc using recent mass-luminosity relations. These are, however, increasingly uncertain at the faint end. We have shown that uncertainties in photometric transformations alone are enough to jeopardize any reliable conclusion concerning the mass function for  $M \lesssim 0.3 M_\odot$  stars. At higher masses, our limited dataset allows us to conclude that the derived  $\omega$  Cen and 47 Tuc mass functions are significantly different, the former being much flatter than the latter. In spite of the uncertainties in the derivation of the PDMF, it is tempting to discuss what the best available estimates of the PDMF can teach us about the IMF and dynamical history of globular clusters. The PDMFs of N6397 and M15 have been shown to be very similar and flattened at the low-mass end (Paresce *et al.* 1995, De Marchi & Paresce 1995a). The present work and that of De Marchi & Paresce (1995b) suggest a flattened PDMF for 47 Tuc as well but with a different shape. These differences in shape between M15 and N6397 on one side and 47 Tuc on the other have been discussed by De Marchi & Paresce (1995b). These authors suggest that they may reflect metallicity-dependent variations in the IMF of these clusters; dynamical effects would be relatively unimportant at locations not far from the half-mass radius and would have been expected to affect the 3 clusters in significantly different ways. However, the best estimate of the  $\omega$  Cen PDMF by Elson *et al.* (1995) does not seem to corroborate this scenario of a metallicity dependent, flattened IMF, with little or no role played by subsequent evolution. Alternatively, the steep PDMF

of  $\omega$  Cen suggests a steep IMF and a dynamically unevolved system with at best a hint of depletion of low-mass stars at large radii, as attested by the differences at the low-mass end between the two  $\omega$  Cen fields studied. In this case, if we are to assume a universal IMF, the data on N6397, M15 and 47 Tuc would point towards substantial dynamical evolution in these clusters even at  $\sim r_h$ , leading to depletion of low-mass stars.

Given the spread in metallicity of the available HST data from this work, Elson *et al.* (1995), von Hippel *et al.* (1995) and the works of De Marchi, Paresce and collaborators, we were able to investigate any trend in the locus of the main sequence as a function of chemical abundance. A trend is clearly seen in the sense that at a fixed luminosity, metal rich stars are redder than metal poor ones for a fixed luminosity. Metal poor CMDs are also steeper than metal rich ones. Once the data are transformed into the standard photometric system, the HST main-sequences seem to agree well with earlier ground-based works, at least for metal rich systems. The disk main sequences of Stobie *et al.* (1989) and Monet *et al.* (1992) are in close agreement with those of N2420 and N2477 derived using HST. The slope of the main-sequence of N3201, a globular cluster studied by Brewer *et al.* (1993), is also in agreement with the HST calibration, although the intercept is about 0.5 mag too bright. We also find a significant discrepancy between the main-sequence fits to the globular clusters observed with HST and those of ground-based subdwarfs; these latter have much flatter CMDs than the former. These discrepancies may either indicate problems in the HST calibration for metal poor stars or reflect real differences between the globular cluster and field halo stellar populations.

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**Table 1.** *47 Tuc* – *ωCen* comparison

LF 1	LF 2	Mag. Range	N1	N2	P
47 Tuc F1	47 Tuc F2	5.5-9.5	530	392	0.4403
47 Tuc F1	47 Tuc F2	5.0-10.0	628	485	0.7404
<i>ω Cen</i> F1	<i>ω Cen</i> F2	5.0-9.0	2616	713	0.3892
<i>ω Cen</i> F1	<i>ω Cen</i> F2	4.3-9.5	3338	911	0.5231
<i>ω Cen</i> F1	<i>ω Cen</i> F2	4.3-10.0	3938	1037	0.0373
<i>ω Cen</i> F1	<i>ω Cen</i> F2	4.3-10.3	4572	1145	0.00005
47 Tuc	<i>ω Cen</i> F1	5.0-8.5	673	2061	0.1447
47 Tuc	<i>ω Cen</i> F2	5.0-8.5	675	560	0.7168
47 Tuc	<i>ω Cen</i> F1	5.0-9.5	1059	3185	0.0390
47 Tuc	<i>ω Cen</i> F2	5.0-9.5	1058	864	0.4163
47 Tuc	<i>ω Cen</i> F1	5.0-10.0	1191	3773	0.00002
47 Tuc	<i>ω Cen</i> F2	5.0-10.0	1192	993	0.1568
47 Tuc	<i>ω Cen</i> F1	5.0-7.0	265	870	0.0463
47 Tuc	<i>ω Cen</i> F2	5.0-7.0	266	226	0.6599

**Table 2.** *47 Tuc*/ $\omega$ *Cen* – N2477 comparison.

LF 1	LF 2	Mag. Range	N1	N2	P
<i>47 Tuc</i>	N2477	7.9-10.0	715	26	0.2278
$\omega$ <i>Cen</i> F1	N2477	7.9-10.0	2317	26	0.3075
$\omega$ <i>Cen</i> F2	N2477	7.9-10.0	623	26	0.5516

**Table 3.** Fits to the main sequence of several clusters and field populations.

Cluster	$[Fe/H]^1$	Range	$a^2$	$b^2$
HST CMDs				
M15	-2.26	$6 < M_V < 8.5$	5.1	2.3
M15	-2.26	$8.5 < M_V < 11.5$	7.5	-0.5
$\omega$ Cen	-1.6	$6 < M_V < 9$	4.6	2.5
$\omega$ Cen	-1.6	$9 < M_V < 12$	5.1	1.7
47 Tuc	-0.6	$6.5 < M_V < 9$	3.1	3.6
47 Tuc	-0.6	$9 < M_V < 12.5$	4.4	1.3
N2420	-0.45	$9 < M_V < 14$	3.6	2.7
N2477	0.00	$9 < M_V < 13$	3.2	2.8
N2477	0.00	$13 < M_V < 15$	3.6	1.6
Ground-Based CMDs				
Disk <sup>3</sup>	--	$10 < M_V < 14$	3.5	2.8
Disk <sup>4</sup>	--	$8 < M_V < 18$	3.3	2.9
N3201 <sup>5</sup>	-1.3	$5.5 < M_V < 8$	4.3	2.1
Halo <sup>3</sup>	--	$11.5 < M_V < 14.5$	3.5	5.4
Halo <sup>6</sup>	--	$6 < M_V < 13$	3.4	4.3
Halo <sup>7</sup>	--	$9.5 < M_V < 14$	3.1	4.5

<sup>1</sup> *Djorgovski (1993), von Hippel et al. (1995)*<sup>2</sup>  $M_V = a (V - I) + b$ <sup>3</sup> *Monet et al. (1992)*<sup>4</sup> *Stobie et al. (1989)*<sup>5</sup> *Brewer et al. (1993)*<sup>6</sup> *Richer & Fahlman (1992)*<sup>7</sup> *Leggett (1992)*



## FIGURE CAPTIONS

- 1- Comparison between the magnitude measurements obtained for the stars in common between 47 Tuc fields 1 and 2 as described in the text. *a)* HST I band magnitudes (F814W filter). *b)* HST V band magnitudes (F606W filter).
- 2- Colour-magnitude diagram for the HST 47 Tuc field studied in this paper.
- 3- The observed luminosity function of 47 Tuc obtained from the combination of the PC data in fields 1 and 2. The data are in the HST F814W system and are not corrected for completeness. Error bars are Poissonian.
- 4- Star completeness functions for fields 1 and 2, obtained from simulations. The error bars incorporate the standard deviation of 5 independent realizations at each magnitude bin and the uncertainty in the quantity  $f_V(I_{814})$  as defined in the text.
- 5- Solid points: completeness-corrected luminosity function for 47 Tuc. The error bars incorporate both Poissonian fluctuations in the number counts and the uncertainty in the completeness function. Open symbols: the 47 Tuc LF derived by De Marchi & Paresce.
- 6- A comparison between the 47 Tuc LF shown in Figure 5 and those derived by Elson *et al.* (1995) for  $\omega$  Cen and Paresce *et al.* (1995) for N6397.
- 7- *a)* The mass function for 47 Tuc as obtained in two different ways: squares utilize the  $M_I - mass$  relation given by De Marchi & Paresce (1995b); triangles make use of the  $M_V - mass$  relation of Bergbusch & Vandenberg (1992) and the  $M_V$  to  $M_I$  conversion of Monet *et al.* (1992). *b)* The 47 Tuc and  $\omega$  Cen mass functions as derived in the present work and in Elson *et al.* (1995), respectively.
- 8- Colour-magnitude diagrams for  $\omega$  Cen (panel *a*), 47 Tuc (panel *b*), N2420 (panel *c*) and N2477 (panel *d*). The data from the later two panels were taken from von Hippel *et al.* (1995) and that in panel *a* are from Elson *et al.* (1995). The data were calibrated to the Johnson-Cousins system using the relations provided by Holtzman *et al.* (1995a,b). Fits to the main sequence of each clusters are shown.

















